THE CROSSWIND SENSITIVITY OF UNLADEN DOUBLES AND TRIPLES COMBINATIONS AND THEIR SUSCEPTIBILITY TO WIND-INDUCED OFFTRACKING AND ROLLOVER

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SUMMARY

A computer-based analysis of large combination vehicles was conducted to examine the likely dynamic response of such systems when exposed to sudden crosswind gusts. The results indicate that relatively large crosswind-related offtracking and roll responses are possible for the so-called "western" triple combination vehicle (27-ft trailers) while travelling at highway speeds under empty and certain partially-loaded conditions. Strong sensitivities of the basic system response were observed for variations in vehicle operating speed, loading configuration, and crosswind magnitude. Additional calculations were also conducted for low speed operations under very high crosswind conditions where "blow-over" of the full-trailers is possible.

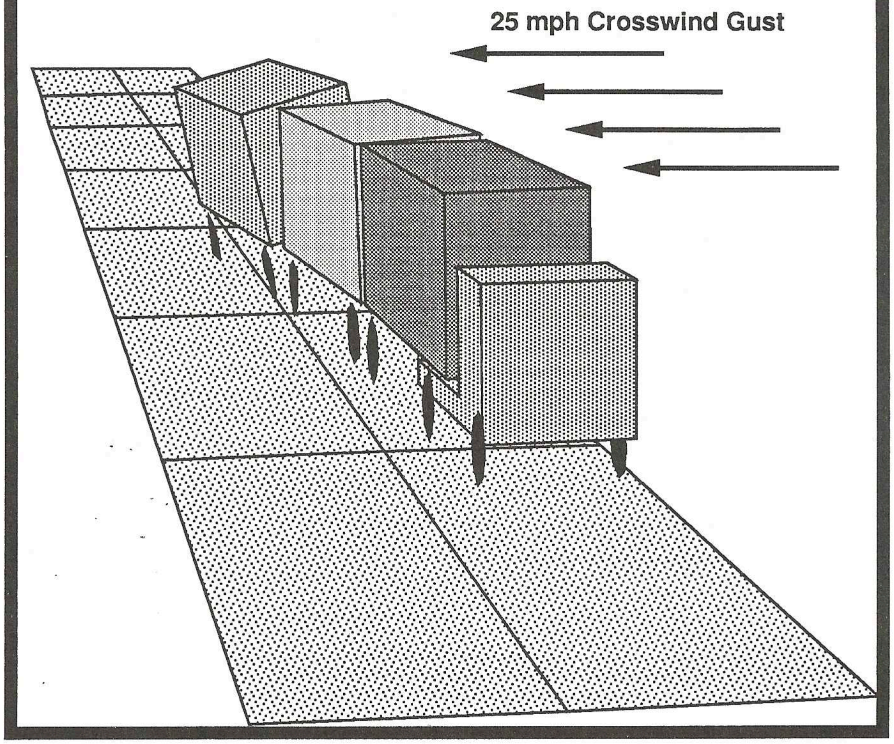
1. INTRODUCTION

Most previous studies of commercial vehicle aerodynamic influences have been concerned with fuel economy issues and methods for reducing longitudinal drag of such vehicles [e.g., 1-2]. These studies have also focused primarily on tractor-semitrailers and straight trucks. The primary issue under examination here — offtracking and possible rollover of rear trailers in combination vehicles due to crosswinds — is not readily available for empirical study or observation from the accident record because of several key factors: (1) the few number of combination vehicles (and particularly triples) operating in the U.S. fleet, (2) the requirement that such vehicles be primarily empty, and (3) the existence of moderate to high crosswind conditions as an excitation. The combination of these three factors helps to explain why unusual dynamic crosswind responses are not widely observed and reported but tend, instead, to be communicated more as "anecdotal information."

The principal focus of this paper is on the dynamic crosswind response of unladen combination vehicles, and particularly, the so-called "western" triple (a three-axle tractor-semitrailer pulling two 27-ft full-trailers connected via A-dollies) principally used in the western portions of the United States. Dynamic offtracking and peak roll response of the rearmost trailer are employed here to characterize the performance of such vehicles when encountering sudden crosswind gusts. The driving scenario used in the analysis is a simple straight-line, driver-regulated, lane-keeping steering control task. Each unit of the combination vehicle train is exposed to a constant-level crosswind in a time-delayed manner similar to that experienced by an actual vehicle emerging from a wind-protected area and moving into an open crosswind. Examples would be vehicles moving out from highway bridge underpasses, tunnel exits, and other abrupt terrain/roadside features into relatively open unprotected areas located along highways.

To illustrate the basic phenomena under study, Figure 1 captures the dynamic response of a "western" triple to a sudden 25 mph crosswind gust at a critical point in the maneuver. As the combination vehicle is exposed to the crosswind gust and responds to the aerodynamic forces and moments imposed on it, the rearmost trailer is "blown" sideways into the adjacent lane of travel. In addition, the front end of the combination vehicle (tractor-semitrailer portion) responds to the same crosswind input by turning into the crosswind (up-wind), thereby necessitating a corrective steering control input by the driver to keep the tractor within the lane boundary. These two combined events: (A) the tractor moving one direction and, (B) the rear trailer in the opposite direction, produces an amplified lateral response for the rearmost trailer. The amplified trailer response presents itself as a significant lateral path excursion (or offtracking response) and an enhanced roll response that can result in wheel lift-offs and possible rollover of the rearmost trailer.

Figure 1. Offtracking and Roll Response of an Empty Triples Combination Travelling at 65 mph.



2. THE DYNAMIC MODEL

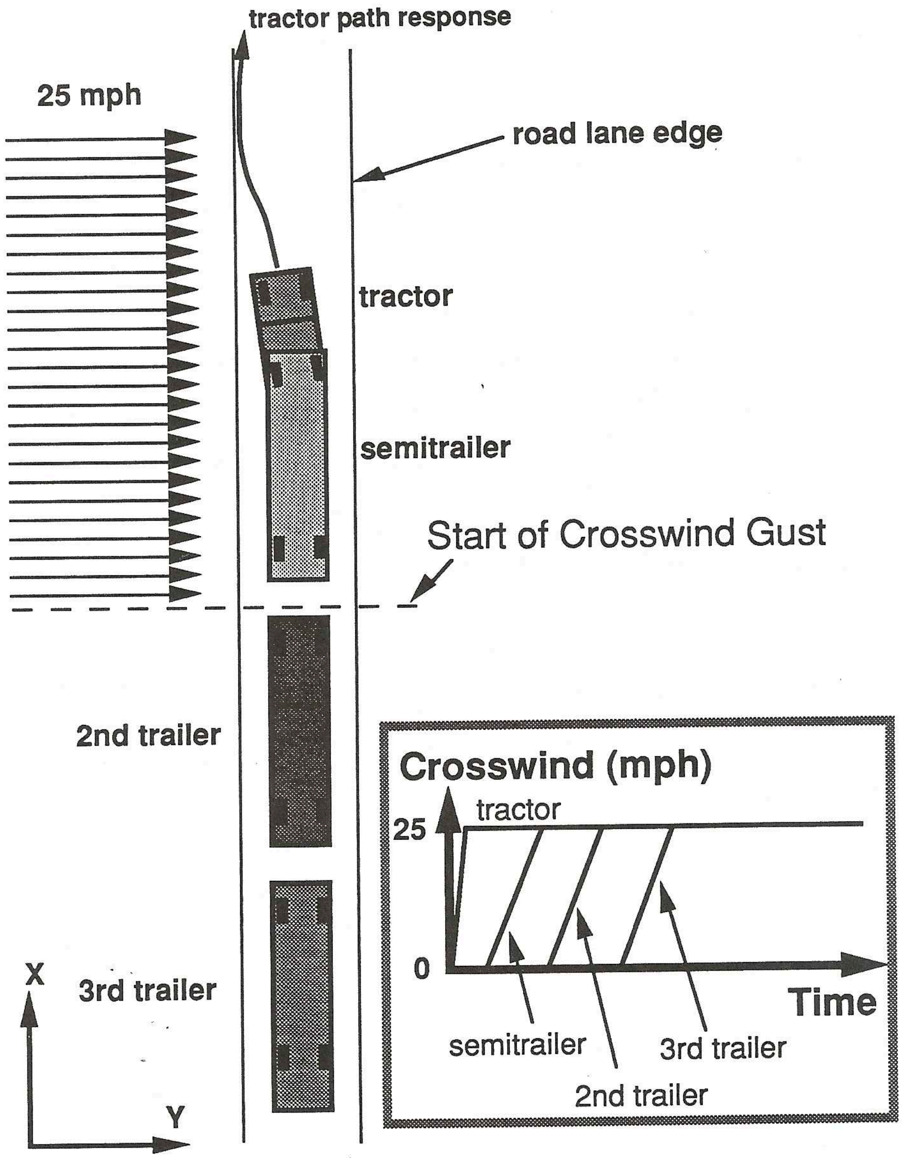
All computer calculations appearing in the paper were conducted using the UMTRI Phase-4 commercial vehicle braking and handling model [3]. The original computer code was modified for this study to include aerodynamic forces and moments for each of the sprung mass bodies. The Phase 4 code treats each sprung mass as having six degrees of freedom. Axle/wheel assemblies each have a vertical and roll degree of freedom. Each wheel also has a rotational spin degree of freedom. The steering system has torsional compliance and is treated in a quasi-static manner. Non-linear tire forces are represented with dependence upon vertical load, forward speed, sideslip, and camber angle. Suspension forces are represented with a semi-empirical force/deflection relationship commonly used to characterize commercial vehicle suspension force measurements. Three aerodynamic forces and three moments act upon each sprung mass and are represented as non-linear tabular data varying with aerodynamic sideslip angle — as typically collected in wind tunnel measurements of ground vehicles. The aerodynamic characterization of the forces and moments acting on the box-like commercial vehicle trailer shapes were based primarily upon four sources of aerodynamic data [1, 4, 5, 6]. (Aerodynamic data for the baseline 27-ft trailer are seen subsequently in Figure 3.) The driver steering control model resident within the Phase 4 program was used here to provide regulatory, human-like steering control for the vehicle model in the presence of the crosswind gust disturbance and is based directly upon the model described in reference [7].

3. THE SIMULATED CROSSWIND MANEUVER

Figure 2 summarizes the nominal crosswind driving maneuver used in the simulation study. The vehicle began each maneuver travelling in a straight-line direction immersed in still-air conditions. The vehicle then entered a step-like stream of crosswind as portrayed in Figure 2. As each unit of the vehicle moves forward, it encounters the crosswind in a time-delayed and sequential manner. The build-up of crosswind is also ramped in over the length of each unit's body as illustrated in the inset diagram of Figure 2. This ramp-like relationship was used to approximate each unit's immersion into the crosswind stream as it moved forward. The rate of immersion (or slope of the ramp) was controlled to correspond with the forward speed of the vehicle train and the length of each unit.

The tractor path response seen in Figure 2 is a result of the the tractor-semitrailer aerodynamics as it first encounters the crosswind. Large aerodynamic side forces, acting on the semitrailer and transmitted to the tractor through the fifth wheel hitch, cause the tractor to initially yaw up-stream into the wind. The driver model then responds to the disturbed tractor response by providing corrective steering back toward the initial travel direction, stabilizing the tractor within the lane. The small "lane-change" path response illustrated in Figure 2 summarizes this sequence of events and is typical of the basic system response seen in most of the simulated runs. The tractor-semitrailer path response and its contribution as an additional excitory steering input to the rear trailers is addressed further in the discussion of conclusions in Section 6.

Figure 2. Simulated Crosswind Maneuver.



4. VEHICLE PROPERTIES & PARAMETER VARIATIONS EXAMINED

The fundamental parameters describing the baseline vehicle configuration (empty 7-axle triple) in this study are given in the following Table 1:

Table 1. Baseline Vehicle Parameters

axle 1 weight: 9124
axle 2 weight: 6326
axle 3 weight: 3750
axle 4 weight: 4750
axle 5 weight: 3750
axle 6 weight: 4750
axle 7 weight: 3750
tractor wheelbase: 10 ft
trailer wheelbase: 21 ft
trailer length: 27 ft
vehicle speed: 65 mph
crosswind: 25 mph
trailer width: 8 ft
trailer box height: 9 ft

Data summarizing the basic aerodynamic properties of each of the 27-ft trailers is seen in Figure 3. These data were derived from a combination of wind tunnel measurements reported in the literature [1, 4, 5, 6]. The first two references provided data in the yaw angle (aerodynamic slip) range of 0 to 30 degrees for box-like and tractor-semitrailer shapes. The next two references provided data for a single box-like van vehicle at yaw angles up to 90 degrees. Consequently, the data seen here for large yaw angles beyond 30 degrees is perhaps less reliable since it was not collected for a specific commercial vehicle shape. However, the basic nature of the data in that range appears to be qualitatively correct. (Aside from a few of the very low speed runs appearing in the paper, most were conducted at speeds of 65 mph with 25 mph crosswinds thereby placing them in the vicinity of 22 degrees of aerodynamic slip.)

The reference point for these wind tunnel measurements is at the mid-point of the trailer length, at ground level. The traditional reference area and length values are seen in Figure 3.

Parameter Variations

A number of variations in loading, weight distribution, aerodynamics, and other vehicle characteristics were examined for the baseline vehicle. In addition, two doubles combination vehicle configurations were also studied for direct comparison with the triples baseline reference vehicle. The following Table 2 identifies each of the parameter variations examined:

Table 2. Parameter Variations

Loading:
- semitrailer loaded
- semitrailer & 2nd trailer loaded
- last trailer only loaded

Tires:
- cornering stiffness increased 20%

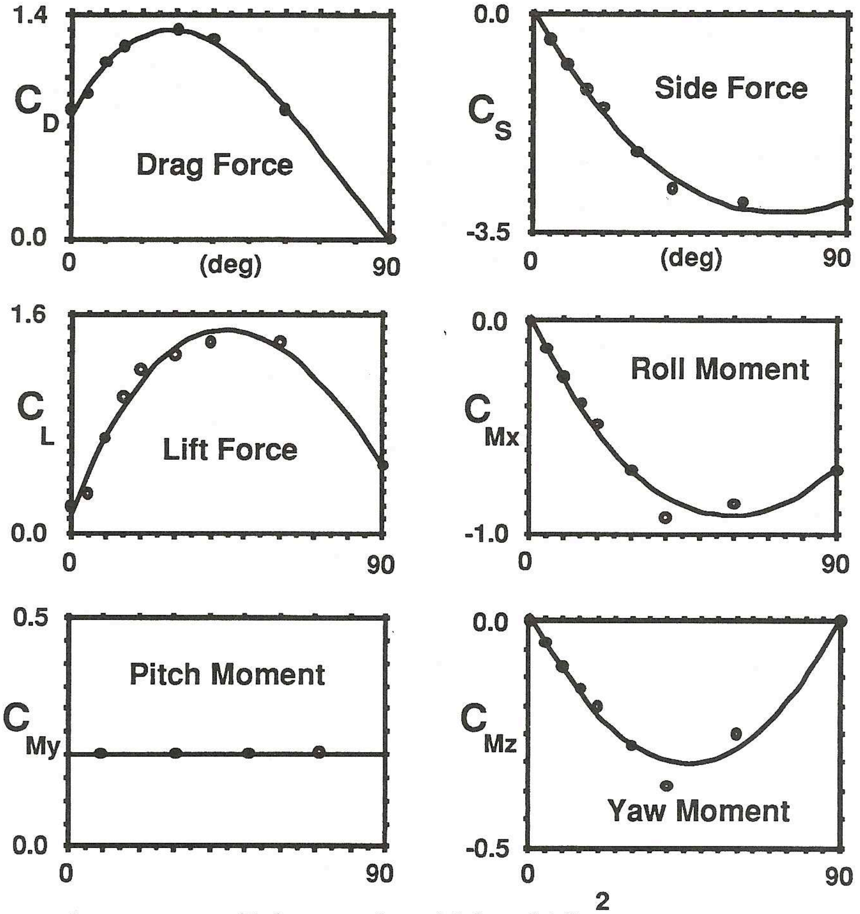
Aerodynamics:
- total aerodynamics reduced 20%
- trailer center of pressure moved rearward 10% to center of trailer box
- aerodynamic lift reduced 20%
- aerodynamic side-force reduced 20%

Weight Distribution:
- 60/40 fore-aft trailer weight distrib
- 40/60 fore-aft trailer weight distrib

Vehicle Speed:
- vehicle speed increased 20%

Configurations:
- "western" double (27-ft trailers)
- "turnpike" double (45-ft trailers)

Figure 3. Estimated Aerodynamic Properties of the 27-ft Trailers. Normalized Coefficients vs. Aerodynamic Slip Angle.



Reference Area (A) = 81 ft^2

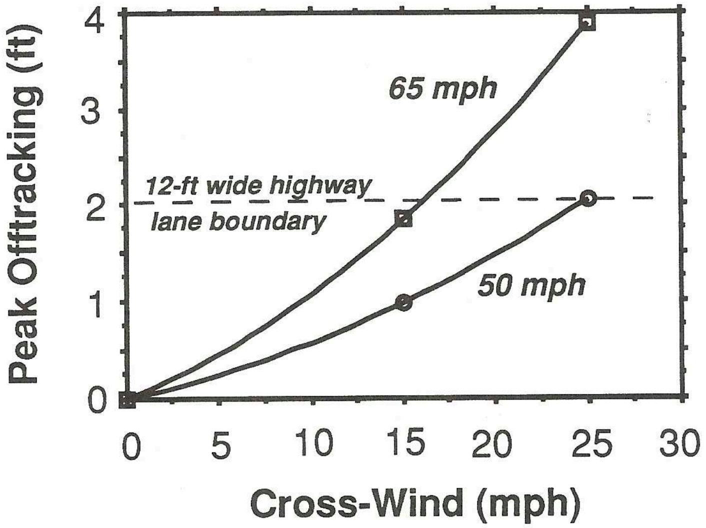
Reference Length (L) = 27 ft

Reference Point is mid-trailer, at ground level.

5. RESULTS

Influence of Vehicle Speed and Crosswind on Peak Offtracking. A series of initial simulation runs were performed with the baseline triples combination vehicle at typical highway speeds in order to map out basic behavioral offtracking characteristics for different levels of crosswind. Figure 4 summarizes these results for the western triple travelling at speeds of 50 mph and 65 mph. The offtracking measure seen here corresponds to the peak lateral displacement of the rearmost corner of the third trailer (from its initial position) as the vehicle responds to the crosswind gust — similar to that seen in Figure 1. The results indicate a significant sensitivity of the peak offtracking performance to both vehicle operating speed as well as crosswind magnitude. Exceedance of a 12-ft wide highway lane boundary is likely for speeds greater than 50 mph and crosswind gusts in excess of 25 mph.

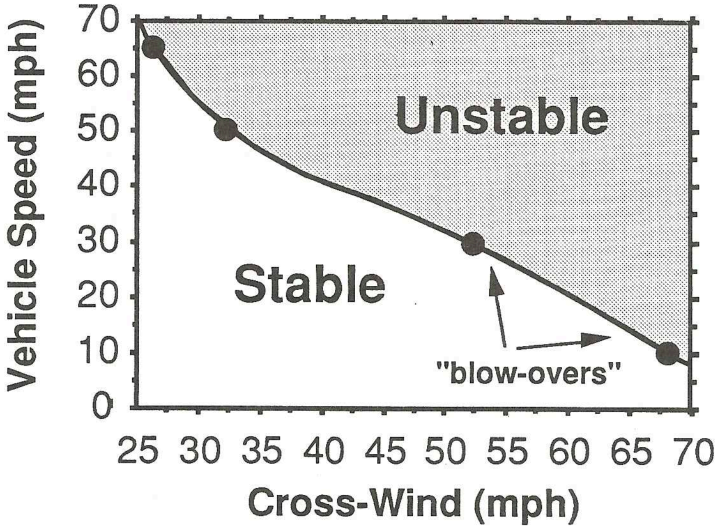
Figure 4. Sensitivity of Peak Offtracking to Magnitude of Crosswind Gust and Vehicle Speed.



Influence of Vehicle Speed and Crosswind on Roll Stability. In order to examine the sensitivity of roll stability to vehicle operating speed and crosswind magnitude, a set of special simulation runs were conducted to identify combinations of vehicle speed and crosswind magnitudes that would produce a rollover event. Figure 5 summarizes these results as a plot that separates the roll-stable and roll-unstable regions. The nature of the rollover event for high speeds (> 40 mph or so) produces a rollover of the rearmost trailer only. The low speed runs exhibited rollover events as "blow-overs" of both full trailers with the second trailer preceding the third trailer in the rollover sequence.

A primary difference between the low-speed and high-speed rollover events was the influence of rearward amplification tendencies in the vehicle train for the high speed runs and its relative absence at lower speeds. The loss of yaw damping with increased forward speed, coupled with the presence of aerodynamic side forces, placed the rearmost trailer in greatest jeopardy as forward speeds increased beyond approximately 40 mph. The low vehicle-speed "blow-over" results of the full-trailer seen on the right-hand side of Figure 5 are also subject to greater uncertainty than the high speed runs since they depend upon the less-accurate, though qualitatively correct, large-yaw-angle aerodynamic data presented in Figure 3. In short, the influence of increased vehicle speed is to enhance rearward amplification tendencies in such vehicles and thereby heighten the likelihood for rearmost trailers in combination vehicles to be significantly affected by crosswind disturbances. These effects are most easily observed as amplified offtracking and roll responses of the rearmost trailer.

Figure 5. Roll Stability of Empty Triples Combination.



Sensitivity of Peak Offtracking and Roll to Vehicle Modifications. The series of vehicle modifications presented previously in Table 2 was applied to the baseline vehicle in order to examine the sensitivity of peak offtracking and roll response of the rear trailer to each parameter variation. Figures 6 and 7 summarizes these results in the form of bar graphs showing the peak offtracking and peak roll angle values accompanying each vehicle modification. The baseline result seen in Figures 6 and 7 shows a peak offtracking value of approximately 4 ft and a near-rollover occurrence with a peak roll angle of approximately 28 degrees. A significant improvement to the total system response is observed if the semitrailer is loaded, or, the first two trailers are loaded. However, in the case of the rearmost trailer being the <u>only</u> loaded unit, performance is then degraded with the trailer exhibiting greater offtracking and ultimate rollover of that unit.

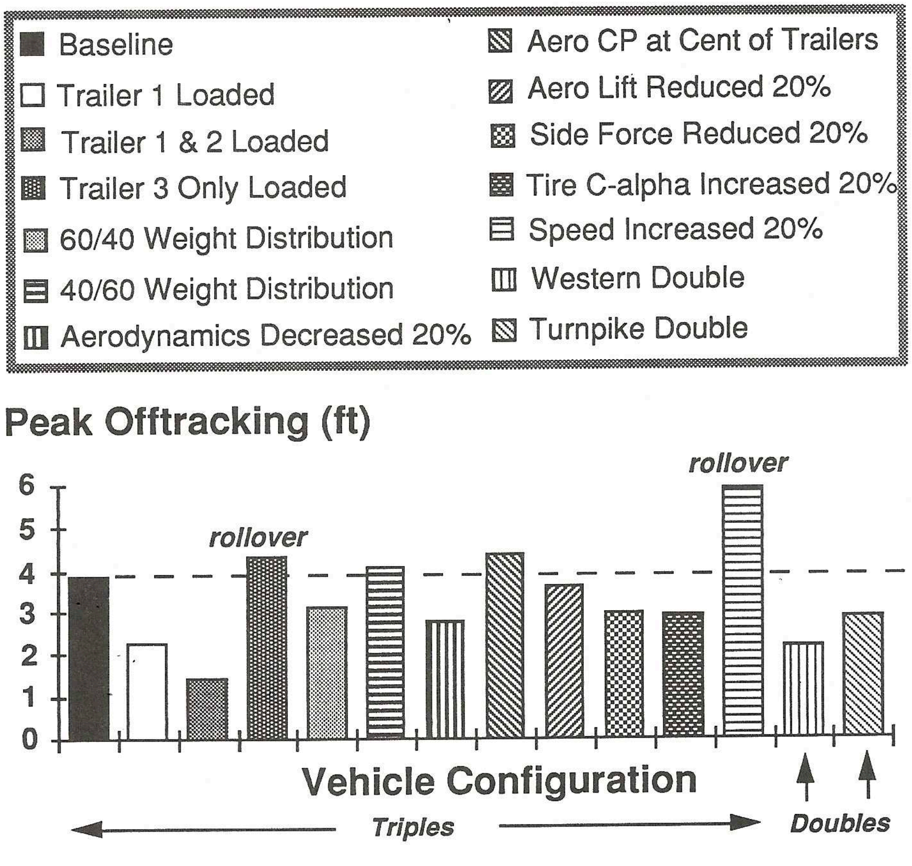
The 40/60 and 60/40 trailer weight distribution runs seen in Figures 6 and 7 bracket the baseline result with the 40/60 weight distribution result showing modest improvement in the system response, and the 60/40 weight distribution a degraded response.

The next four aerodynamic variations all indicate the degree of improvement expected from modest 20% changes in aerodynamic effects (three of which constitute reductions in aerodynamic influence). Offtracking results are likewise improved except for the rearward center-of-pressure variation which locates the aerodynamic CP at the mid-trailer position, instead of at a point 2.7-ft forward (baseline location).

The increased tire cornering stiffness variation resulted in an improvement in both roll stability as well as offtracking. Peak roll response was attenuated by approximately 30% and offtracking was reduced 25%.

The forward speed variation (increase of 20%) produced significant degradation in system performance with a rapid rollover occurrence of the rearmost trailer. A comparable reduction in vehicle speed produced an approximate 40% improvement in peak offtracking (Figure 4.)

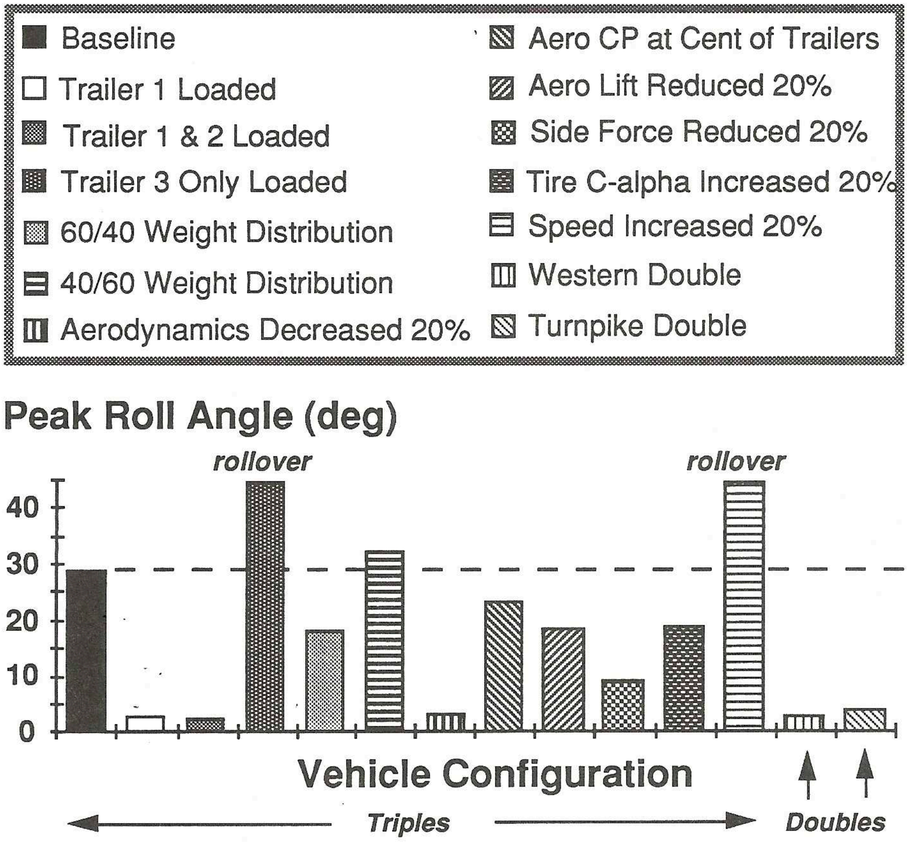
Figure 6. Sensitivity of Peak Offtracking to Vehicle Modifications.



Lastly, two different doubles configurations were simulated to: 1) estimate the degree of improvement obtained by the removal of the third trailer (western double configuration) and, 2) examine the analogous response of a turnpike double having 45-ft trailers and tandem axle suspensions. As seen in Figures 6 and 7, both doubles configurations are considerably more stable in roll compared with the baseline triple, and both show significantly less peak offtracking response in comparison with the triple.

The larger offtracking response for the turnpike double, beyond that observed for the western double, is attributable to the increased wind exposure (larger aerodynamic forces and moments) and overall length (over-hang effect). This occurs despite the stabilizing benefit of additional axles and greater weight enjoyed by the turnpike double.

Figure 7. Sensitivity of Peak Roll Response to Vehicle Modifications.



6. CONCLUSIONS

The results of this study indicate that relatively large crosswind-related offtracking and roll responses are possible for the so-called "western" triple combination vehicle (27-ft trailers) while travelling at highway speeds under empty and certain partially-loaded conditions. Strong sensitivities of the basic system response were observed for variations in vehicle operating speed, loading configuration, and crosswind magnitude.

The nature of the system responses are highly dependent upon forward speed. The high-speed conditions produced considerably reduced damping that, in turn, assisted the aerodynamic forces and moments in disturbing the rearmost trailers to the greatest degree. The inherent rearward amplification tendency present in most combination vehicles at elevated speeds helps to aggravate the offtracking and roll response of the rearmost trailers beyond that observed for similar vehicles operated at lower speeds in even higher crosswind conditions.

The basic mechanism affecting most combination vehicles during a sudden crosswind exposure is illustrated in Figure 8. Seen here is a diagram portraying the static turning response of the tractor-semitrailer (or front-end) portion of a combination vehicle to a crosswind gust. As the semitrailer first enters the crosswind and becomes laterally loaded by the aerodynamic side-force, a reaction force, **F**, is transmitted to the tractor through the fifth-wheel articulation point and produces a reactionary moment, **Mz**, on the tractor. The tractor responds by yawing *into* the wind, producing an *upstream* turning motion of the tractor-semitrailer (unlike the *downstream* response typically observed for passenger cars [8]). The turning motion of the tractor-semitrailer then imparts a steering input to each of the following full-trailers. The steer input to the full trailers, induced by the aerodynamic loading on the tractor-semitrailer, excites a typical transient yaw/path response in the full trailers that is then enhanced further by the aerodynamic forces on the full-trailers as they move forward into the same crosswind. The polarities of the turning response and the aerodynamic side-force / roll moment are collaborative — both tending to rollover the full trailer units.

However, the steering input and aerodynamic side-force have opposing effects with regard to offtracking. The steering input tends to reduce the degree of trailer offtracking induced by the aerodynamic side force. Because of the dynamical delays of the system response in producing steer-related lateral motion of the full trailers, the aerodynamic side-force dominates this battle causing an initial lateral offtracking response of the full trailers in the down-wind direction.

This high-speed mechanism is interesting for combination vehicles since it indicates that a significant amount of the crosswind response of the full-trailers is attributable to the degree to which the tractor-semitrailer front-end portion of the combination vehicle responds to crosswind gusts. This is not the case at lower speeds where: 1) the rearward amplifying tendencies to steer inputs are largely absent, and 2) the offtracking and roll responses of the full trailers are totally dependent upon the aerodynamic properties of the trailers alone.

Another high-speed influence that comes into play is that of driver steering behavior and its effect on the system response, particularly in terms of how the driver compensates for the crosswind yawing moment that the semitrailer imposes on the tractor. An example time history response of driver steering wheel angle for the baseline western triple travelling at 65 mph is seen in Figure 9. The initial negative driver steering response is due to the tractor's encounter with the crosswind, followed by a large positive correction by the driver in attempting to arrest the moment **Mz** imposed on the tractor from the semitrailer's crosswind encounter. The remaining steady-state steering trim angle maintains the tractor within the highway lane in the presence of the constant crosswind. If significantly different driver steering responses were excited by the crosswind gust, notable differences in the system response would appear under high speed conditions. The limited number of simulation runs conducted under this study however, did not reveal a strong sensitivity of the baseline offtracking and roll response of the rearmost trailer to modest changes in driver preview and time delay steering characteristics.

Figure 8. Crosswind Response of Tractor-Semitrailer and the Resulting Steer Input to the Full Trailers.

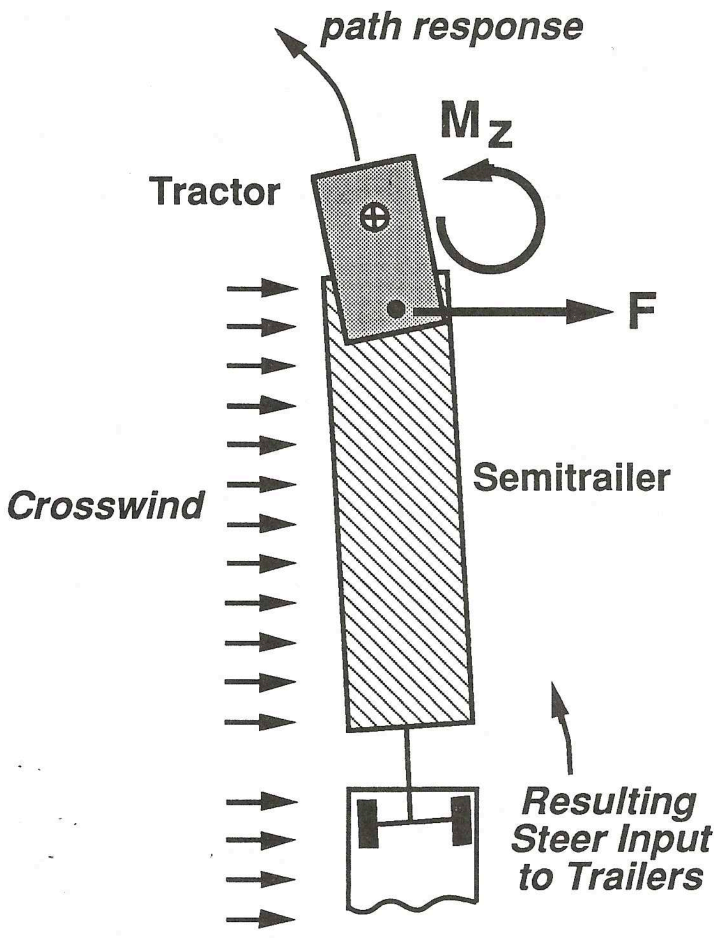
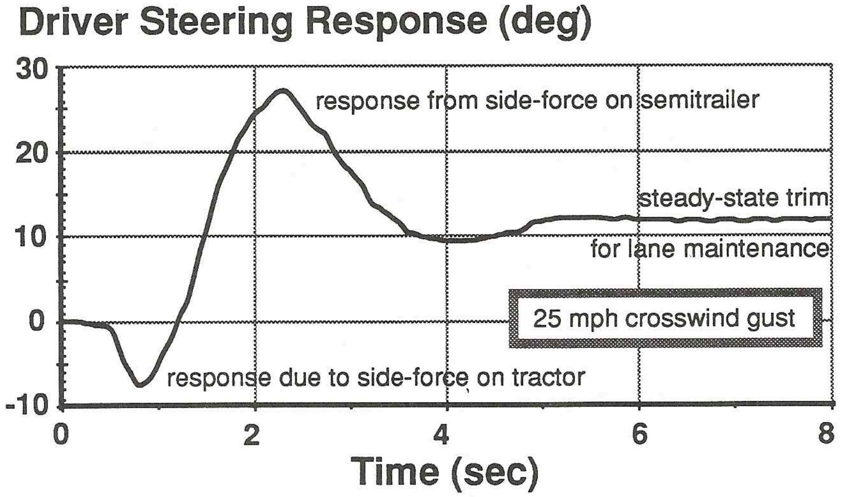


Figure 9. Driver Steering Response — Baseline Triple.



In summary, certain basic observations are noted:

- Unladen western triple combination vehicles travelling at highway speeds in excess of 50 mph and encountering a 25 mph gust of crosswind can exhibit offtracking magnitudes that will cause encroachment by the rearmost trailer into adjacent lanes.
- Corresponding roll behavior of the rearmost trailer under such operating conditions can exhibit marginal roll stability.
- System response at elevated speeds is particularly sensitive to changes in vehicle speed and crosswind magnitude.
- An effective "immunization" against degraded rear trailer performance in crosswinds is accomplished by loading the semitrailer, or, the semitrailer and the first full-trailer.
- Loading of only the rearmost trailer further degrades performance and increases the likelihood of a rear trailer rollover.
- Altering the empty trailer fore/aft weight distribution to a 60/40 percentage (without altering the fore/aft aerodynamic CP location of the trailer) improves the basic crosswind sensitivity; an opposite 40/60 fore/aft weight distribution produces a degraded system performance.
- 20% reductions in all aerodynamic forces and moments or corresponding changes in lift or side-force alone, all result in at least 25% improvements in peak offtracking and roll response of the last trailer.
- Rearward movement of the trailer aerodynamic center-of-pressure to a mid-trailer position (from its baseline position located 10% ahead of the trailer mid-point),

improves the roll stability of the rearmost trailer, but degrades its peak offtracking performance.

- 20% increases in tire cornering stiffnesses produced 25-30% improvements in offtracking and roll response of the rearmost trailer.

- The western double (the western triple with last trailer removed) displays approximately half the amount of rearmost (2nd) trailer offtracking than that displayed by the rearmost (3rd) trailer in the western triples combination. Considerably smaller peak roll angle responses were also recorded.

- The turnpike double combination vehicle (45-ft trailers) exhibits approximately two-thirds as much peak offtracking for its rearmost (2nd) trailer than that observed for the last (3rd) trailer in the baseline triples combination. Peak roll response for the rearmost trailer in the turnpike double was also significantly reduced.

- At low vehicle operating speeds, "blow-over" of empty full-trailers can occur under very high crosswind conditions (see Figure 5). For the baseline triple combination examined here, both full trailers were overturned, with the lead full-trailer normally preceding the last full-trailer in the rollover sequence.

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